

A MAGNETOHYDRODYNAMIC MODEL OF THE M87 JET  
I: SUPERLUMINAL KNOT EJECTIONS FROM HST-1 AS TRAILS OF QUAD RELATIVISTIC MHD SHOCKSMASANORI NAKAMURA<sup>1</sup>Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218  
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## ABSTRACT

This is the first in a series of papers that introduces a new paradigm for understanding the jet in M87: a collimated relativistic flow in which strong magnetic fields play a dominant dynamical role. Here we focus on the flow downstream of *HST*-1 — an essentially stationary flaring feature that ejects trails of superluminal components. We propose that these components are quad relativistic magnetohydrodynamic shock fronts (forward/reverse fast and slow modes) in a narrow jet with a helically twisted magnetic structure. And we demonstrate the properties of such shocks with simple one-dimensional numerical simulations. Quasi-periodic ejections of similar component trails may be responsible for the M87 jet substructures observed further downstream on  $10^{2-3}$  pc scales. This new paradigm requires the assimilation of some new concepts into the astrophysical jet community, particularly the behavior of slow/fast-mode waves/shocks and of current-driven helical kink instabilities. However, the prospects of these ideas applying to a large number of other jet systems may make this worth the effort.

*Subject headings:* individual: M87 — galaxies: active — galaxies: jets — methods: numerical — MHD

## 1. INTRODUCTION

M87 is a nearby giant elliptical galaxy (Virgo A, 3C 274, NGC 4486) located at the center of the X-ray-luminous Virgo cluster (Fabricant et al. 1980), host of the first extragalactic jet discovered (Curtis 1918). The one-sided jet emerging from the nucleus of M87, where a  $3.2 (\pm 0.9) \times 10^9$  solar mass black hole<sup>3</sup> resides (Macchetto et al. 1997), has been well-studied on a wide range of wavelengths from radio to X-rays (Owen et al. 1989; Biretta et al. 1995; Perlman et al. 1999; Biretta et al. 1999; Junor et al. 1999; Marshall et al. 2002; Wilson & Yang 2002; Perlman & Wilson 2005; Harris et al. 2006; Ly et al. 2007; Kovalev et al. 2007). Because of its proximity ( $D = 16$  Mpc; Tonry 1991), which gives a linear scale of  $78$  pc arcsec<sup>-1</sup>, the M87 jet is one of the best candidates to investigate relativistic outflows in extragalactic systems.

One of the most remarkable features of the M87 jet is the innermost bright knot G, lying about  $1''$  from the core in the *Very Large Array* (VLA) observations (Owen et al. 1989). That region has been resolved by *Hubble Space Telescope* (HST) into a structured complex known as *HST*-1 (Biretta et al. 1999). It is located around  $0.8$ - $1''$  (projected) from the core (or  $\sim 260 - 320$  pc de-projected for a viewing angle of  $\sim 14^\circ$ ; Wang & Zhou 2009). It appears almost stationary, but component velocities downstream of the complex are highly relativistic, with a range  $4c - 6c$  (Biretta et al. 1999). Indeed, the component of *HST*-1 that is furthest upstream (i.e., *HST*-1d) is stationary to within the er-

rors ( $< 0.25 c$ ), and has been identified as the point of origin of the superluminal ejections (Cheung et al. 2007). As of this writing, no other observations have detected any superluminal components upstream of the *HST*-1 complex. Therefore, the observations obtained up to now, paint a surprising picture: no evidence for highly relativistic velocities between the core and *HST*-1, a stationary knot at *HST*-1d, and then, suddenly, superluminal motion of components immediately downstream of *HST*-1.

The structure of the jet downstream of *HST*-1 ( $1 - 18''$  or  $0.1 - 1.5$  kpc in projected distance) can be characterized by trailing clumps or knots of bright gas (*HST*-1 to C) with an apparent deceleration to subluminal speeds (around  $6c$  to  $0.5c$ ) (Biretta et al. 1995, 1999) and filamentary structures (“wiggles/kinks”) (Owen et al. 1989; Sparks et al. 1996). The high overpressure in the synchrotron gas and the highly polarized helical filaments (Owen et al. 1989; Perlman et al. 1999) indicate the existence of underlying ordered magnetic fields with a 3-dimensional helix seen in projection; magnetic fields, therefore, appear to play a role in determining the M87 jet structure even on large scales. The magnetic field vectors in the knots *HST*-1, D, A, and C are perpendicular to the jet direction, indicating the presence of longitudinal compression by a shock front and/or a tightly wound magnetic helix (Owen et al. 1989; Perlman et al. 2003). Detailed broadband (from radio through optical to X-ray) spectral shape of the knots (*HST*-1 to C) in the M87 jet favors the scenario in which synchrotron emission dominates the radiation and *in situ* particle acceleration (by the first-order Fermi process) almost certainly occurs in the large scale M87 jet (both within knots and outside them) (Perlman & Wilson 2005).

The purpose of the paper is to investigate the dynamics downstream of *HST*-1 using relativistic magnetohydrodynamics (MHD). We introduce here the concept that the superlu-

<sup>1</sup> Allan C. Davis Fellow<sup>2</sup> NASA Postdoctoral Fellow<sup>3</sup> Recently, a new black hole mass of  $6.4 (\pm 0.5) \times 10^9 M_\odot$  has been proposed by Gebhardt & Thomas (2009); however we use  $3 \times 10^9 M_\odot$  throughout the paper.

minimal components in M87, and perhaps extragalactic jets in general, are the result of MHD shocks produced in helically twisted, magnetized relativistic outflows. Our exclusive focus here on the flow just downstream of *HST*-1, a unique dynamical behavior of a pair of sub/super-luminal knots, constitutes the first in a series of papers on the MHD paradigm for the entire M87 jet. The paper is organized as follows. We outline our model in §2. In §3 our numerical method is introduced, and in §4 we show our numerical results. Discussions and conclusions are given in §5.

## 2. MODEL DESCRIPTION

We propose an MHD model of the M87 jet that extends beyond, or downstream, of *HST*-1 that resolved by the VLA and HST observations ( $1 - 18''$  or  $0.1 - 1.5$  kpc in projection). The structure of the jet downstream of *HST*-1 can be characterized by a conical shape  $z \propto r$  (where  $r$  is a jet radius and  $z$  is a distance from the nucleus) with an opening angle of  $\theta_{\text{open}} \sim 6^\circ$  (de Vaucouleurs & Nieto 1979; Owen et al. 1980; Reid et al. 1982; Owen et al. 1989). The high degrees of radio and optical polarization in both the knot (40%–60%) and interknot (20%–40%) regions (Perlman et al. 1999) indicate the presence of coherent magnetic fields (highly ordered) on large scales associated with the underlying jet.

Under the assumption of the minimum energy condition, the knots themselves appear to be significantly overpressured (Owen et al. 1989) with respect to the ambient thermal gas (Young et al. 2002), but the interknot regions do not (Sparks et al. 1996). In order to maintain a conical streamline of the adiabatic jet within a uniform ambient gas (an isothermal King profile with a core radius  $R_c \simeq 18''$ ), the fields may have to be much stronger and more highly ordered (*i.e.*, a force-free configuration with a 3-dimensional helix) than a weak and tangled field at the equipartition level ( $\sim$  a few of  $100 \mu\text{G}$ ). Magnetic fields, therefore, appear to play a crucial role in determining the structure of the M87 jet even on larger scales over 100 pc.

In the present paper, we do not examine the entire three dimensional structure of the M87 jet, described in §1; this will be treated in forthcoming papers. Instead, we focus on the unique properties of the ejected superluminal components (Cheung et al. 2007) by using a simple one dimensional approach. Cheung et al. (2007) reported that some time between 2005 December and 2006 February, one of the newly ejected components, called *HST*-1c, *split into two bright features*: a faster moving component (c1:  $4.3c \pm 0.7c$ ) and a slower moving (c2:  $0.47c \pm 0.39c$ ). If the bright knot is a shock, then such a pair of separated components naturally can be identified as forward/reverse modes. We here model this interesting feature by relativistic MHD simulations. In addition, we suggest that a similar expansion might be occurring in earlier *HST* observations (*HST*-1e:  $6.00c \pm 0.48c$  / *HST*-1 East:  $0.84c \pm 0.11c$ ) by Biretta et al. (1999).

Furthermore, the Knot D complex located just downstream of the *HST*-1 complex, also displays distinct features (DE – DM – DW) with different propagation speeds and a sideways oscillation of the brightness ridge-line (Biretta et al. 1995). It has been pointed out that four quasi-periodic knot complexes downstream of *HST*-1 (called D, E, F, and I) are at roughly uniform spacing (Biretta & Meisenheimer 1993). Thus, recurrent ejections of superluminal components at the *HST*-1d site may happen with a certain quasi-periodic time scale. We suggest that these bright components can be considered as similar paired structures to *HST*-1c2/c1 and *HST*-1 East/e: DE

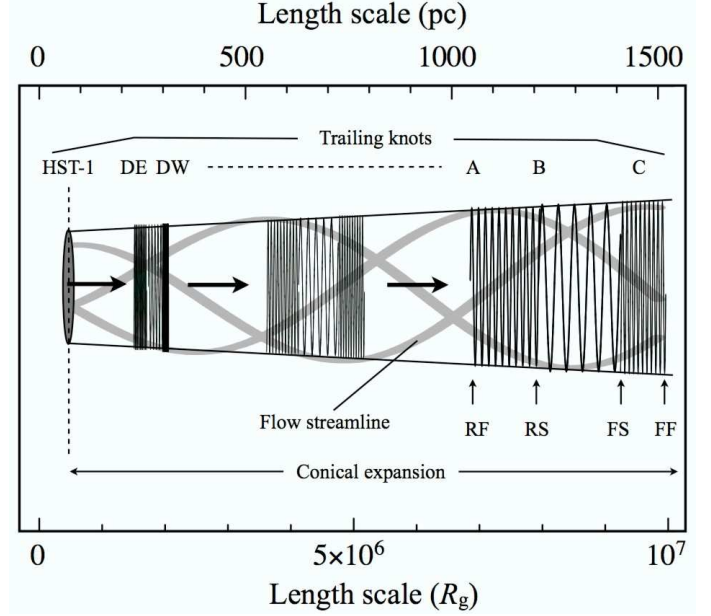


FIG. 1.— Schematic view of our model of the 87 jet in the VLA scale. The structure of the jet downstream of *HST*-1 can be characterized by trailing MHD quad shocks that may be intermittently generated at the *HST*-1 complex. The system of MHD quad shocks consists of the forward fast (FF) and slow (FS) followed by the reverse slow (RS) and fast (RF) shocks.

– DM – DW, E – EF, F – I, and A – B – C further downstream [refer to Owen et al. (1989) and Biretta et al. (1999) for definitions of the knot labels].

The stationary knot in *HST*-1d may be identified as the recollimation shock (Stawarz et al. 2006; Bromberg & Levinson 2009). Once the recollimation shock is formed at a finite distance, the reflection of supersonic flows may emit a shock component downstream of the recollimation point. A Steady model of relativistic MHD multi-layer outflows (relativistic jet and non-relativistic wind) by Gracia et al. (2009) nicely reproduces such observed properties of M87 as an asymptotic collimation (Junor et al. 1999) with a feature brightened at around 100 pc (projected distance) by an over-collimating MHD flow.

Of particular interest is the brightest emission structure A – B – C. As reported by Owen et al. (1989) and Perlman et al. (1999), knots A and C have certain similarities: i) bright transverse linear features (normal to the jet axis) indicative of a shock front (Biretta et al. 1983); ii) dominance of transverse magnetic field suggesting ordered helical magnetic components. Visible side-to-side oscillation is also observed between these knots, and magnetic vectors appear to follow the fluctuating jet axis in this part (including knot B).

We point out a sudden enhancement of emission at knot A, at the *upstream* edge of that knot, indicating a reverse shock and a rapid drop in emission at the *downstream* edge of knot C, suggesting that it is the corresponding forward shock (see, Figure 8a, 10a of Owen et al. 1989). Particle acceleration is associated with both the forward and reverse modes. In addition, the substructure between the upstream edge of knot A and the downstream edge of knot C indicates there may be another pair of (forward/reverse) shocks or rarefaction waves. The downstream edge of knot A or knot B may be a reverse mode feature, while the upstream of knot C may be a forward mode feature.

Sudden changes in magnetic vector orientation strongly im-

ply the existence of MHD fast/slow mode waves. The transverse component of the magnetic field  $B$  ( $B_\perp$ ) increases across a fast mode front (the normal component  $B_\parallel$  remains unchanged through an MHD oblique shock and thus the magnetic pressure  $p_m$  increases), while  $B_\perp$  decreases across a slow mode front ( $p_m$  decreases). Thus, we interpret the brightest emission structure A – B – C to be a trail of *quad* relativistic MHD shocks (forward fast/slow and reverse slow/fast) (perhaps, two slow modes can be rarefaction waves) generated in a helically twisted super-fast magnetic flow. Such a flow can be generally expected at further downstream from the AGN in the MHD jet theory and emissions of MHD shocks from the stationary knot feature has been inspected by MHD simulations of strongly magnetized jets (Lind et al. 1989). The presence of four shocks, *instead of two*, is due to the presence of  $B_\phi$ , which serves a role equivalent to  $B_\perp$  in the simpler planar oblique shock case.

The transverse field component is dominant in some knots (HST-1, D, A, and C), indicating strong longitudinal compressions by a passing shock. In the past, a transverse orientation of the magnetic field was thought to be due to longitudinal compression of roughly random (tangled) magnetic fields (*weakly polarized*) by a hydrodynamic-like shock (Laing 1980) (*i.e.*, this is essentially a *perpendicular* shock). However, as is shown in Perlman et al. (1999), the high degree of polarization is confirmed in interknot regions of the M87 jet on scales of  $10^{2-3}$  pc. So the classical picture of a weak, random jet magnetic field may be in conflict with these observations. It is natural to conclude, therefore, that underlying magnetic fields in both the interknot and knot regions are systematically ordered with helical (longitudinal + azimuthal) components (three-dimensional helical structure). Longitudinal compression of a helical magnetic field also will produce an enhanced azimuthal (*i.e.*, projected transverse) component.

High energy particle acceleration by the first-order Fermi process is generally believed to occur in extragalactic jets (Blandford & Ostriker 1978). A relativistic particle energy distribution [ $n(E) \propto E^{-\delta}$ ] steeper than  $\delta = 2$  would be needed to produce the radio - optical - X-ray synchrotron spectrum in the M87 jet. Synchrotron model fits from radio through optical to X-ray data produce  $\delta = 2.2$  at all energies and all locations along the jet (Perlman & Wilson 2005) and about  $\delta = 2.36$  on average (Liu & Shen 2007). These agree very well with the conditions needed for a diffusive shock acceleration (DSA) [ $\delta = 2 - 2.5$ ; Kirk & Dendy (2001)].

The geometry of a perpendicular MHD shock (this is a so-called “magneto-acoustic shock”, a particular case of the fast-mode MHD oblique shock with only magnetic component along the shock surface  $B_\perp$ ) is not suitable for a DSA; negligible particle acceleration has been confirmed by PIC simulations (Langdon et al. 1988; Gallant et al. 1992). Furthermore, in the standard picture of Fermi acceleration, the DSA does not work for slow-mode MHD shocks because the magnetic field strength decreases across them, and therefore they cannot act as magnetic mirrors for the upstream particles. Thus, *only fast-mode MHD oblique shocks are probably responsible for the observed non-thermal emissions.*

In summary, we suggest that each pair of bright knots on  $10^{2-3}$  pc scales in the M87 jet is a quasi-periodic event produced in the stationary HST-1d knot as a consequence of re-collimation processes of a converging super-fast magnetosonic jet. They are trailing quad MHD shock wave fronts (forward fast/slow modes and reverse slow/fast modes), which propa-

gate as super/sub-luminal components in a *highly magnetized and twisted*, relativistic outflow powered by a non-linear torsional Alfvén wave train (Meier et al. 2001). A schematic view of our M87 model is shown in Figure 1.

The physics of MHD shocks in helically twisted magnetized flows are still not very well known in the astrophysical jet community. Despite the fact that jet dynamics is inherently three-dimensional, much of the physics of these jets can be obtained from simple 1-D simulations of flow along a cylindrical shell. Therefore, in this paper we investigate observed properties of *HST-1c* (Cheung et al. 2007) using a simple one-dimensional approach that suffices in illustrating the basic principles. We demonstrate that observed proper motions of forward (superluminal) and reverse (subluminal) knots can be reproduced precisely in our relativistic MHD simulation model.

### 3. NUMERICAL METHOD

Based on observations (see, *e.g.*, Owen et al. 1989; Perlman et al. 1999), we assume that the magnetic field plays a fundamental role in determining the flow properties of the M87 jet all the way up to scales beyond 100 pc in projection. We impose axisymmetry and choose a cylindrical coordinate system ( $r, \phi, z$ ) whose axis coincides with the symmetry-axis. We model the dynamical behavior of observed *HST-1c* knot which split into two distinct features as sub/super-luminal knots (Cheung et al. 2007). We here consider initial phase of the knot ejection and separation (propagation of individual knots with constant speeds) and thus dynamics of the flow can be described in so-called 1.5-dimensional approximation along a cylindrical shell of radius  $r_0$  (which is assumed to be rigid), which allows the quantities to vary in the  $z$ -direction, and which also allows for the influence of azimuthal effects.

Our system obeys ideal, special relativistic MHD (Lichnerowicz 1967) that consists of the baryon mass and energy-momentum conservation laws in the absence of a gravitational field, Maxwell equations in CGS-Gaussian units, and Ohm’s law:

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial z} = 0, \quad (1)$$

$$Q \equiv \begin{bmatrix} \gamma \rho \\ \gamma^2 h V_\phi / c^2 - E_r B_z / (4\pi c) \\ \gamma^2 h V_z / c^2 + E_r B_\phi / (4\pi c) \\ B_\phi \\ \gamma^2 h - p + (E_r^2 + B_\phi^2 + B_z^2) / (8\pi) \end{bmatrix}, \quad (2)$$

$$F(Q) \equiv \begin{bmatrix} \gamma \rho V_z \\ \gamma^2 h V_\phi V_z / c^2 - B_\phi B_z / (4\pi) \\ \gamma^2 h V_z^2 / c^2 + p + (E_r^2 + B_\phi^2 - B_z^2) / (8\pi) \\ c E_r \\ \gamma^2 h V_z + c E_r B_\phi / (4\pi) \end{bmatrix} \quad (3)$$

The above equations denote the mass, the azimuthal ( $\phi$ ) momentum, the axial ( $z$ ) momentum, the azimuthal induction, and the energy equations respectively.

Here  $\rho$  and  $p$  are the rest-mass density and gas pressure in the fluid frame.  $V = (V_\phi, V_z)$  is the fluid velocity and  $\gamma$  is the associated Lorentz factor  $\gamma \equiv 1/(1 - V^2/c^2)^{1/2}$ .  $c$  is the speed of light, and  $\Gamma = 5/3$  is the specific heat ratio.  $B = (B_\phi, B_z)$  denotes magnetic field as measured in the laboratory (galaxy) frame. (Note that  $B_z$  is constant by  $\nabla \cdot B = 0$  and never changes in time.)  $h = \rho c^2 + \Gamma p / (\Gamma - 1)$

is the relativistic enthalpy, and  $E_r [= (V_\phi B_z - V_z B_\phi)/c]$  is the radial component of the electric field as measured in the laboratory frame.

We normalize physical quantities by unit length scales  $L_0$ , density  $\rho_0$ , velocity  $V_0$  in the system, and other quantities derived from their combinations, e.g., time as  $L_0/V_0$ , etc. This normalization does not change the form of the basic equations. A factor of  $4\pi$  has been absorbed into the scaling for both  $E_r$  and  $B$ . The resulting set of time-dependent, fully conservative equations for Special Relativistic MHD (SRMHD) is solved by a finite volume method (FVM). We use a newly designed, hybrid flux (HF) scheme (Nakamura 2010) that consists of a unique hybridization of a Godunov-type and centered difference-based fluxes to achieve low-level numerical diffusion. (Typical 1-D Riemann problems exhibit  $\delta^{\text{HF}}/\delta^{\text{HLL}} \approx 0.6$  and  $\delta^{\text{HF}}/\delta^{\text{Roe}} \approx 0.7$ , where  $\delta$  is the relative error determined from an  $L_1$  norm). MUSCL-TVD reconstruction (van Leer 1979) and MUSCL-Hancock predictor-corrector time marching (van Leer 1984) schemes, with a van Albada limiter (van Albada et al. 1982), are implemented to maintain second-order accuracy in both space and time.

#### 4. NUMERICAL RESULTS

We adopt  $r_0 = 1$  pc as the unit length  $L_0$  (and as the radius of *HST*-1d) and  $c = 3 \times 10^{10}$  cm s $^{-1}$  as unit velocity  $V_0$ . An electron density  $n_e = 0.17$  cm $^{-3}$  and a temperature  $kT = 0.8$  keV at the Bondi radius  $\sim 120$  pc (Allen et al. 2006) are taken as central ISM properties. These correspond to a density  $\rho_{\text{ISM}} (= \mu m_p n_e) = 1.7 \times 10^{-25}$  g cm $^{-3}$  ( $m_p$  is the proton mass and  $\mu = 0.61$  is the molecular weight for full ionization) and temperature  $T_{\text{ISM}} = 9.3 \times 10^6$  K. We also assume a unit density  $\rho_0 = 1.7 \times 10^{-27}$  g cm $^{-3}$ , which is two orders smaller than  $\rho_{\text{ISM}}$  (light jets are generally believed to be present in radio galaxies and quasars) (see, e.g., Krause 2003). This gives  $\rho_0 c^2 = 1.5 \times 10^{-6}$  dyn cm $^{-2}$  as the unit pressure. The unit time  $t_0$  becomes  $r_0/c = 10^8$  s = 3.2 yr, and the unit magnetic field  $B_0$  is  $(4\pi\rho_0 c^2)^{1/2} = 4.3$  mG.

The computational domain  $z \in [-0.04, 2.0]$  (pc in a dimensional scale) is resolved with 5100 grid points. A Riemann problem, which possesses two uniform initial states (l: left and r: right) separated at  $z = 0.0$ , is considered to investigate the evolution of the system. Our fiducial model consists of a super-fast magnetosonic, relativistic jet inflow ( $\gamma \simeq 6.22$ ) into a nearly force-free, weakly twisted ( $B_\phi/B_z \simeq 0.33$ ) medium flowing with a sub-relativistic speed ( $\gamma \simeq 1.07$ ). It produces a set of quad relativistic MHD shocks. The following initial conditions are prescribed:

$$(\rho, V_\phi, V_z, B_\phi, B_z, p)^l = (1.0, 0, 0.987, 0.8, 2.4, 0.256)$$

on the left-hand side ( $-0.04 \leq z \leq 0.0$ ) and

$$(\rho, V_\phi, V_z, B_\phi, B_z, p)^r = (1.0, 0, 0.36, 0.8, 2.4, 0.256)$$

on the right-hand side. Time integration, using a CFL number of 0.8, is followed until  $t = 2.0$  ( $\sim 6.4$  yr) to examine the earliest phases of relativistic MHD shock propagations.

The above choice of initial values has been inferred carefully from various observational constraints. By assuming a viewing angle  $\theta_v \sim 14^\circ$  at *HST*-1 (Wang & Zhou 2009), a maximum pattern speed of a faster moving component *HST*-1c1 (including an error) can be estimated from its apparent speed  $\beta_{\text{app}} = 4.3c \pm 0.7c$  (Cheung et al. 2007) as

$$\beta_{\text{pattern}} = \frac{\beta_{\text{app}}}{\beta_{\text{app}} \cos \theta_v + \sin \theta_v} \simeq 0.982, \quad (4)$$

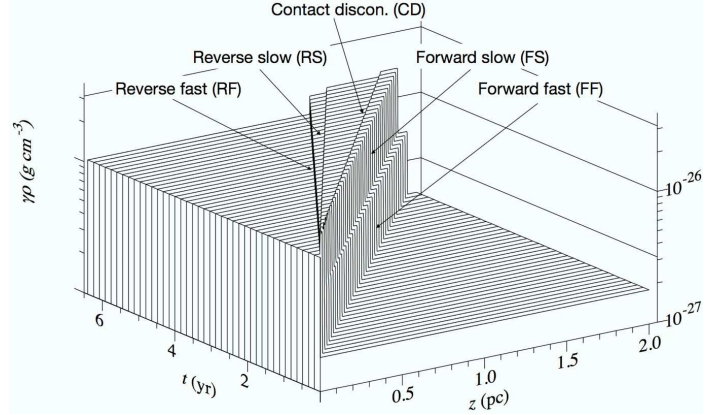


FIG. 2.— Space-time ( $z, t$ ) diagram of logarithm of the proper density  $\gamma\rho$  (vertical axis), as measured in the laboratory (galaxy) frame. Quad MHD shocks; FF, FS, RS, and RF, and a contact discontinuity (CD) are labeled.

where  $\beta = V/c$ . It would seem far more natural to have the pattern speed tied to the jet fluid speed, with  $\beta_{\text{pattern}} \lesssim \beta_{\text{fluid}}$  (Biretta et al. 1995). We note  $\beta_{\text{pattern}} = 0.989$  corresponds to  $\theta_v = 19^\circ$ , an upper limit of the viewing angle for possible solutions to have the superluminal motion  $\beta_{\text{app}} = 6.0$  as seen in *HST* observations (Biretta et al. 1999). On the other hand, an ambient motion in the vicinity of *HST*-1 complex can be constrained by the stationary feature of *HST*-1d with  $\beta_{\text{app}} < 0.25$  (Cheung et al. 2007) as  $\beta_{\text{pattern}} < 0.516$ . The magnetic field vectors in projection around *HST*-1 are perpendicular to the jet direction and the timescale of optical and X-ray variability of *HST*-1 requires  $|B| \sim 10$  mG (Perlman et al. 2003). Taking into account a viewing angle, the constraint for the projected  $B$ -vectors to be perpendicular to the jet can be expressed (Asada et al. 2008) as

$$\frac{B_\phi}{B_z} > \sin \theta_v \simeq 0.24. \quad (5)$$

Thus, our simulation model is reasonably guided by observations. In the following, we examine our results.

Figure 2 shows the propagation of MHD wave fronts in the proper density  $\gamma\rho$ . Quad MHD shocks and a contact discontinuity (CD or entropy wave), all with constant speeds, are clearly visible. Relative to a reference frame that co-moves, and co-rotates, with the jet plasma near the CD, these waves propagate in both the forward (F) and reverse (R) directions. Here we adopt the convention of counting shocks beginning with the one farthest from the origin of the disturbances (*HST*-1). Two of the four shocks, the first and the fourth, are forward fast-mode (FF) and reverse fast-mode (RF) shocks, respectively. The other two, the second and the third, are forward slow-mode (FS) and reverse slow-mode (RS) shocks.

Snapshots of various quantities at  $t = 2.0$  are illustrated in Figure 3. As seen in (a) and (b), the gas is compressed across the first (FF) and second (FS) shocks. In crossing the third shock (RS) the gas is expanded by a smaller ratio than the FS, while it is expanded much more strongly in crossing the last (RF) shock rather than the FF as clearly shown in (b) [it may not be visible in (a), but this is due to the frame of the measurement; in the rest frame of fluid elements, the distribution of  $\rho$ , instead of  $\gamma\rho$ , has a similar tendency with  $p$ ]. As a result, the gas accumulates in the region between the second and third shocks. As one moves from large to small  $z$ ,  $\gamma$  increases with gradual steps throughout the first, second, and

third shocks, but largely increases at the last shock towards the injection level  $\gamma \simeq 6.22$  shown in (c). Similarly, from (d),  $B_\phi$  increases across the first shock, decreases across the second one, increases again across the third shock, and finally decreases across the fourth one. From (e),  $V_\phi$  changes as well, in a way consistent with the increased twist between the first and the second shocks, and reversed between the third and fourth shocks.<sup>4</sup>

We define the plasma- $\beta$  (a ratio of the gas pressure to the magnetic pressure) in the rest frame of the fluid element:

$$\beta_p \equiv \frac{2p}{B_z^2 + B_\phi^2/\gamma^2}. \quad (6)$$

This enables us to compare the importance of the magnetic forces with the plasma forces in the proper rest frame of the fluid. As shown in (f), the unshocked region further downstream of the FF is highly magnetically dominated  $\beta_p \simeq 0.08$ , which is prescribed as the initial condition.  $\beta_p$  increases slightly in crossing the FF (both the gas and magnetic pressures are enhanced similarly). However the accumulated gas region (RS-CD-FS) is heated strongly (the gas pressure increases, while the magnetic pressure decreases) and thus attains near equipartition ( $\beta_p \sim 1.4$ ). At the forward part of the shock quad (FS-FF)  $\beta_p$  is still very small ( $\sim 0.1$ ), but at the reverse part (RF-RS) it has increased by nearly one order ( $\sim 0.9$ ). In the region behind the shock quad, after the four MHD shocks have passed,  $\beta_p$  decreases to a low level that is prescribed in the initial condition. Given the fact that the relevant physical quantity is the fluid frame value of the plasma- $\beta$  ( $\beta_p$ : eq. 6), and that  $B_\phi/B_z < 1$ ,  $\beta_p$  is not appreciably different from that in the initial values adopted in the galaxy frame. Note that the relativistic length-contraction effect produces a weak compression of the structures between FS-FF rather than between RF-RS when viewed in the laboratory frame (which is also the computational grid on which the simulation is done).

Strengths and propagation speeds of the four shocks remain constant with distance as they propagate in our coordinate system: axial propagation ( $z$ -direction) in a uniform medium (constant sound and Alfvén speeds) in a fixed-radius cylindrical shell. Individual speeds are estimated as  $V_{FF} \sim 0.97 c$ ,  $V_{FS} \sim 0.94 c$ ,  $V_{RS} \sim 0.73 c$ , and  $V_{RF} \sim 0.67 c$ , respectively. For a viewing angle of  $\theta \sim 14^\circ$  at *HST*-1 (Wang & Zhou 2009), the faster component *HST*-1c1 has  $\sim 0.97 c$ , while the slower component *HST*-1c2 has  $\sim 0.67 c$ . As is mentioned in §2, a separation of observed super/subluminal components can be identified as distinct proper motions of two fast-mode MHD shocks,  $V_{FF}$  and  $V_{RF}$ . Therefore, our numerical model is reasonably consistent with observations (Cheung et al. 2007) at a quantitative level.

We performed a simulation with an underlying velocity (the left state in the Riemann problem we solve) that was constrained by the maximum velocity of the *HST*-1d ( $< 0.25c$ ) allowed by the observations. There is no evidence for an additional underlying flow other than the velocity of the *HST*-1d component itself. That is, the flow that produces the superluminal motion of *HST*-1c1 is the flow, and that is our model: the ejection of a new MHD jet from *HST*-1 at a speed much greater than any underlying flow is what produces the recent observations of *HST*-1 complex suggested by Cheung et al.

<sup>4</sup> Note that the region FF - FS and the region RS - RF are counter-rotating when viewed from a frame that rotates with the plasma near the CD.

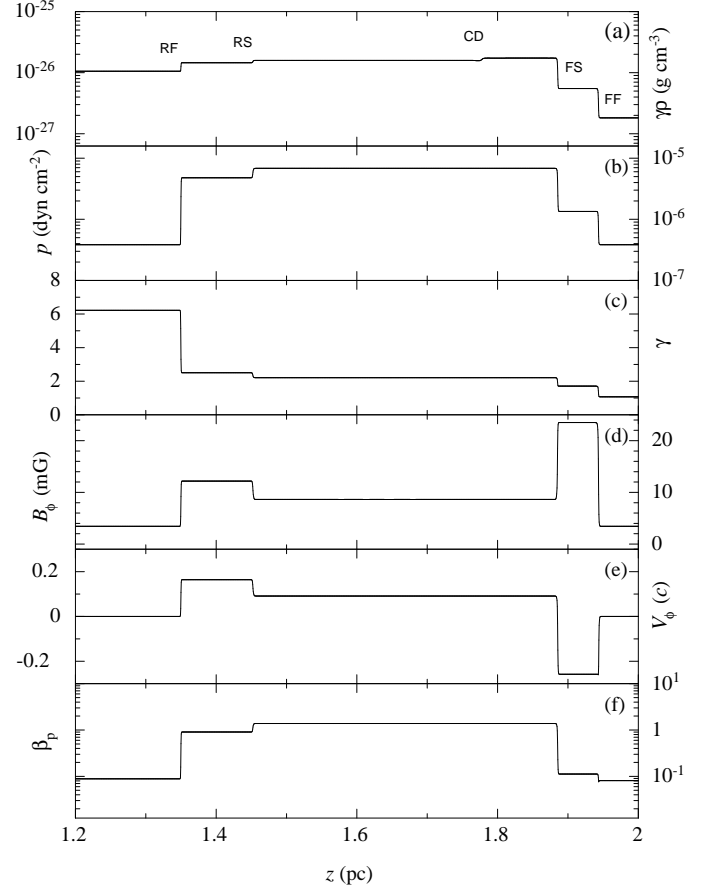


FIG. 3.— (a)-(f)  $\log(\gamma\rho)$ ,  $\log(p)$ ,  $\gamma$ ,  $V_\phi$ ,  $B_\phi$ , and  $\beta_p$  (plasma- $\beta$ ), respectively, shown at  $t = 2.0$ . Only the region  $1.2 \leq z \leq 2.0$  is displayed. Note that panels (a)-(e) are measured in the rest frame of the galaxy, but the panel (f) is measured in the rest frame of fluid element. Each discontinuity is labeled in (a) (see also Fig. 1).

(2007). The FF shock that mainly determines the Lorentz factor for the *HST*-1 complex is *HST*-1c1. What we learn from the observations is that the RF shock (*HST*-1c2) is subluminal; a property predicted by the quad shock model. This constitutes a constraint despite the fact that the exact speed of the RF shock is determined by the model parameters which have been specified only within a given range. However, we emphasize that a very wide range of those parameters predicts sub-luminal motion for the RF shock.

In a forthcoming paper, we will study the propagation of quad relativistic MHD shocks in a conical geometry ( $z \propto r$ ) with an increasing cross section that is compatible with the M87 jet on  $10^{2-3}$  pc scales. This will allow us to study deceleration of the shocks as the jet propagates on  $10^{2-3}$  pc scales (Biretta et al. 1995, 1999).

## 5. DISCUSSION AND CONCLUSIONS

Figure 4 shows the variations in the magnetic helical lines of force over  $\sim 1$  radian of the  $\phi$ - $z$  plane as the jet (propagating in the  $z$  direction) passes through each of quad MHD shocks. Magnetic field strengths  $|B|$  in the regions upstream of RF (⑤) and downstream of FF (①) are about 10.9 mG ( $B_\phi/B_z \simeq 0.33$ ). As mentioned above, the azimuthal field components in the inter-shocked regions are amplified by compression, and they dominate over the axial component in



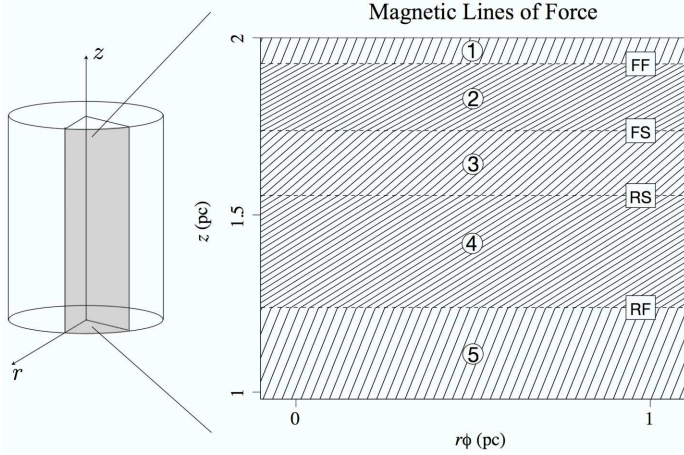


FIG. 4.— Variation of the helical magnetic field in the  $\phi$ - $z$  plane ( $B_\phi$ ,  $B_z$ ) and in the frame of the galaxy, as the jet flow (in  $z$ ) crosses the quad MHD shocks (labeled at right). (Compare the right-hand panel with Fig. 3e.) Only  $\sim 1$  radian of the pattern is shown, which, of course, is periodic over the full  $2\pi$  radian circumference of the cylinder. The pitch angles of the field upstream of the RF and downstream of the FF (both are “shock-upstream”) are equal (in this frame). Changes in the pitch angle are caused by jump conditions at the different shocks. Each state between quad MHD shocks is identified by numbers

the rest frame of the galaxy;  $B_\phi/B_z$  and  $|B|$  are  $\sim 2.3$  and  $\sim 25.7$  mG (FS – FF: ②),  $\sim 1.2$  and  $\sim 16.0$  mG (RF – RS: ④), respectively. On the other hand, in the rest frame of the fluid element, only the forward part of inter-shocked region (FS–FF: ③) has large magnetic pitch ( $B_\phi/\gamma/B_z \sim 1.3$ ).

One of the important insights that we derive from our numerical model is an asymmetric structure of inter-shocked regions such as gas compression and magnetic pitch angle  $\theta'_{\text{pitch}} [\equiv \tan^{-1}(B_\phi/\gamma/B_z)]$  (in the rest frame of the fluid element) in pre-shock regions of the two fast shocks:  $\theta'_{\text{pitch}} \sim 17^\circ$  downstream of the FF (①), and  $\sim 3^\circ$  upstream of the RF (⑤) ( $\theta_{\text{pitch}}$  in the frame of the galaxy is same at the downstream of the FF and the upstream of the RF, as is shown in Fig. 4). Efficiencies and mechanisms of relativistic particle acceleration depends crucially on both the magnetization and the magnetic obliquity of the upstream plasma. Particle acceleration is mostly mediated by DSA for quasi-parallel shocks ( $\theta'_{\text{pitch}} \lesssim 10^\circ$ ), but shock drift acceleration (SDA) is the main acceleration mechanism for larger magnetic obliquity (Sironi & Spitkovsky 2009). In the rest frame of the fluid element, the density increases by  $r_{\text{cmp.}} \simeq 3.42$  at the RF and  $r_{\text{cmp.}} \simeq 1.90$  at the FF (where  $r_{\text{cmp.}} \equiv \rho_2/\rho_1$  is the shock compression ratio and  $\rho_{1,2}$  are the density ahead and behind the shock). The slope  $\delta$  in the particle energy distribution for DSA is determined as  $\delta = (r_{\text{cmp.}} + 2)/(r_{\text{cmp.}} - 1)$  (Bell 1978) and thus  $\delta \simeq 2.23$  is expected at the RF, which agrees to the theory and observation described in §2. In a forthcoming paper, we will examine these aspects (DSA/SDA) in details to identify observed properties of the M87 jet in  $10^{2-3}$  pc scales as a context of quad relativistic MHD shock system.

As mentioned in §2, the flow downstream of *HST-1* has a conical structure with a constant opening angle until it reaches knot A. Poloidal magnetic field varies as  $B_z \propto r^{-2}$  in this region, while toroidal magnetic field varies as  $B_\phi \propto r^{-1}$ . With measured radii  $r_0 \sim 1$  pc near *HST-1d* (Cheung et al. 2007) and  $r_1 \sim 33.2 - 44.1$  pc at knot A (Owen et al. 1989; Sparks et al. 1996), combined with the  $B$ -field strengths

( $B_\phi \sim 12.39$  mG and  $B_z \sim 10.32$  mG) at the reverse feature (RF – RS: ④) in the simulation, we estimate  $B_{\phi 1} \sim 280.9 - 373.2 \mu\text{G}$  and  $B_{z1} \sim 5.3 - 9.4 \mu\text{G}$  as a counterpart of knot A. This strongly toroidally dominated field agrees with the polarization observations (Owen et al. 1989; Perlman et al. 1999). Using the upper limits on inverse Compton radiation imposed by the HESS and HEGRA Cerenkov telescope observations of the kpc scale jet to estimate the magnetic field strength in the brightest knot A, Stawarz et al. (2005) obtain a “safe” lower limit of  $|B| \gtrsim 300 \mu\text{G}$ , indicating a departure from the equipartition value (from the synchrotron spectrum of the knot A); the magnetic field energy density within the brightest knot is very likely higher than the energy density of the radiating ultrarelativistic electrons. This implies that interknot regions are likely to be extremely magnetized. On the other hand, a reasonable upper limit to the field strength of knot A can be constrained by the total power  $L_j$  of the M87 jet from the relation  $\pi r_1^2 (\mathbf{V} \times \mathbf{B}) \times \mathbf{B} / (4\pi) \leq L_j/2$ , where  $L_j \sim \text{few} \times 10^{44} \text{ erg s}^{-1}$  (Owen et al. 2000), and we assume an equipartition between the matter energy and Poynting fluxes. In a situation in which  $V_z \simeq c > V_\phi \gg V_r$ ,  $B_\phi \gg B_z > B_r$ , the dominant term in the axial ( $z$ ) direction, the main carrier of electromagnetic energy, is  $B_\phi^2 V_z / (4\pi) \simeq B_\phi^2 c / (4\pi)$ . This gives  $|B| (B_\phi) \leq 1$  mG. Thus, these constraints are consistent with our derivation  $|B| \sim 289 - 370 \mu\text{G}$  at around knot A by considering an expansion of jet cross section.

Sideways oscillations of the brightness ridge-lines downstream of the *HST-1* complex are closely followed by the filamentary structure of distributed magnetic fields (Owen et al. 1989). Some of these filaments can be interpreted as a 3-dimensional helix seen in projection, produced by growing current-driven instabilities (CDIs) (Nakamura et al. 2001). Indeed, Nakamura & Meier (2004) found that MHD shocks play an important role in triggering helical kink CDIs: while rotation of the plasma may stabilize the helical kink instability locally, MHD shocks (particularly in the region A – B – C) can rapidly alter this stabilizing rotation (Figure 3), suddenly causing the magnetized plasma to violate the Kruskal-Shafranov stability criterion. Further downstream of knot C, the knot-like features disappear, and the jet becomes diffusive with strong side-to-side oscillations and bending. This may also be a good example of the growing “external mode of the CDIs beyond the X-ray cluster core where a separation of the paths between the jet forward and return current occurs due to the rapidly decreasing density of the external thermal gas” (Nakamura et al. 2007). We shall examine the above topics in forthcoming papers by treating our quad MHD shock model in 1-D conical and, eventually fully 3-D, flow environments.

The idea that magnetic fields are instrumental in the formation and propagation of jets in active galactic nuclei dates back four decades. Despite a recent growing consensus on this notion stemming from the results of numerical simulations of magnetohydrodynamic flows near black holes, the precise dynamical role of magnetic fields in observed parsec and kilo-parsec jets has remained uncertain. In this first in a series of papers, we have combined SRMHD numerical simulation with observation to explain superluminal knot ejections from *HST-1* in the M87 jet. Indeed this is the first examination of superluminal motions in the extragalactic jet as a consequence of trailing MHD shocks in a relativistic flow that possesses helically twisted magnetic structures. We begin to develop a detailed picture for the jet in M87 that is grounded in the dynamics of relativistic MHD, ultimately suggesting that the

entire jet (from subparsec to kiloparsec scales) is an MHD phenomenon. Eventually our model may also be readily applicable to other jet systems, and it may constitute the foundation of an MHD paradigm for astrophysical jets in general.

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